HELAC-NLO

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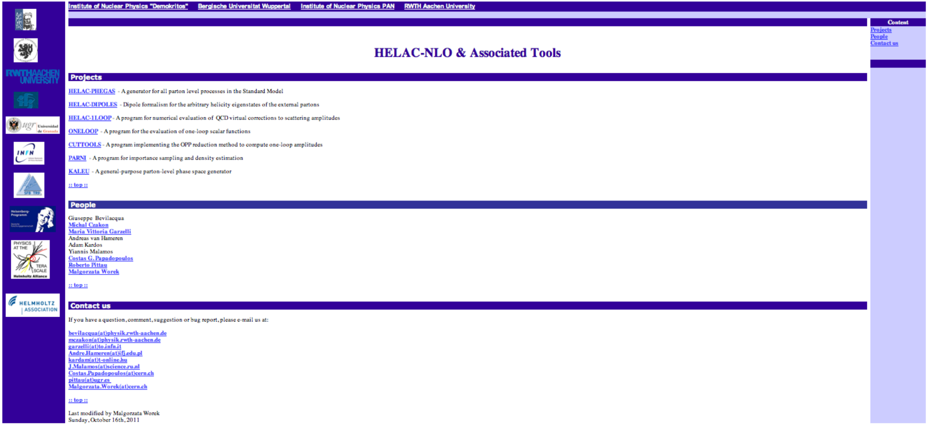
&
CERN, Geneva, Switzerland

CERN 2012, October 1, 2012

HELAC PAGE

http://helac-phegas.web.cern.ch/helac-phegas/



HELAC-NLO & Associated Tools

Projects

HELAC-PHEGAS - A generator for all parton level processes in the Standard Model

HELAC-DIPOLES - Dipole formalism for the arbitrary helicity eigenstates of the external partons

HELAC-1LOOP - A program for numerical evaluation of QCD virtual corrections to scattering amplitudes

ONELOOP - A program for the evaluation of one-loop scalar functions

CUTTOOLS - A program implementing the OPP reduction method to compute one-loop amplitudes

PARNI - A program for importance sampling and density estimation

KALEU - A general-purpose parton-level phase space generator

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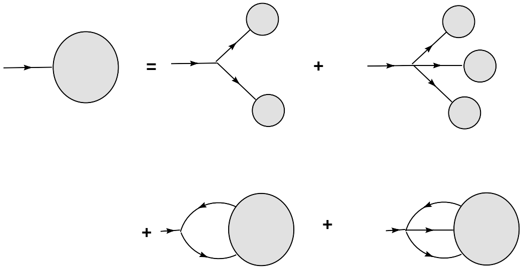
Last modified by Malgorzata Worek
Sunday, October 16th, 2011

DYSON-SCHWINGER RECURSIVE EQUATIONS

- 1999 `HELAC`: The first code to calculate recursively tree-order amplitudes for (practically) arbitrary number of particles

A. Kanaki and C. G. Papadopoulos, Comput. Phys. Commun. **132** (2000) 306 [arXiv:hep-ph/0002082].



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C. G. Papadopoulos, Comput. Phys. Commun. **137** (2001) 247 [arXiv:hep-ph/0007335].

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- For QCD color connection representation: revival of the 't Hooft ideas ('71) in the modern era. Citation Alert !

HELAC COLOR TREATMENT

$$\mathcal{M}^{a_1,i_2,\dots,i_k}_{j_2,\dots,j_k} t^{a_1}_{i_1 j_1} \to \mathcal{M}^{i_1,i_2,\dots,i_k}_{j_1,j_2,\dots,j_k}$$

$$\mathcal{M}^{i_1,i_2,\dots,i_k}_{j_1,j_2,\dots,j_k} = \sum_{\sigma} \delta_{i_{\sigma_1},j_1} \delta_{i_{\sigma_2},j_2} \dots \delta_{i_{\sigma_k},j_k} A_\sigma$$

gluons → (i,j), quark → $(i,0)$, anti-quark → $(0,j)$, other → $(0,0)$

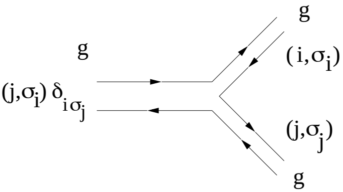
$$\sum_{\{i\},\{j\}} |\mathcal{M}^{i_1,i_2,\dots,i_k}_{j_1,j_2,\dots,j_k}|^2$$

$$\sum_{\sigma,\sigma'} A^*_\sigma \mathcal{C}_{\sigma,\sigma'} A_{\sigma'}$$

$$\mathcal{C}_{\sigma,\sigma\prime} \equiv \sum_{\{i\},\{j\}} \delta_{i_{\sigma_1},j_1} \delta_{i_{\sigma_2},j_2} \dots \delta_{i_{\sigma_k},j_k} \delta_{i_{\sigma'_1},j_1} \delta_{i_{\sigma'_2},j_2} \dots \delta_{i_{\sigma'_k},j_k} = N_c^{m(\sigma,\sigma\prime)}$$

HELAC COLOR TREATMENT

Color-connection Feynman Rules



HELAC TREE ORDER CURRENT VERSION

- 2007 `HELAC`: http://helac-phegas.web.cern.ch/helac-phegas/

  A. Cafarella, C. G. Papadopoulos and M. Worek, Comput. Phys. Commun. **180** (2009) 1941 [arXiv:0710.2427 [hep-ph]].

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- 2007 `HELAC`: http://helac-phegas.web.cern.ch/helac-phegas/
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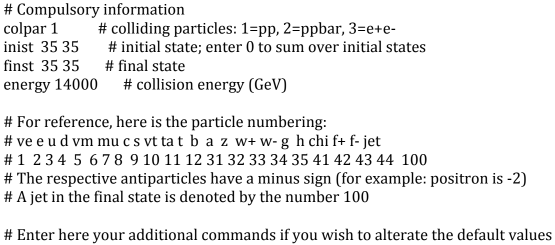
- Very easy to use: just edit the `user.inp` file and then execute the command `./run.sh`



```
# Compulsory information
colpar 1         # colliding particles: 1=pp, 2=ppbar, 3=e+e-
inist  35 35       # initial state; enter 0 to sum over initial states
finst  35 35      # final state
energy 14000      # collision energy (GeV)

# For reference, here is the particle numbering:
# ve e u d vm mu c s vt ta t  b  a  z  w+ w- g  h chi f+ f- jet
# 1  2 3 4  5  6 7 8  9 10 11 12 31 32 33 34 35 41 42 43 44  100
# The respective antiparticles have a minus sign (for example: positron is -2)
# A jet in the final state is denoted by the number 100

# Enter here your additional commands if you wish to alterate the default values
```

HELAC TREE ORDER CURRENT VERSION

- 2007 `HELAC`: http://helac-phegas.web.cern.ch/helac-phegas/
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- Including kt-reweight for jet matching
- Latest: $W + 5$ jets at LHC

NLO

$$d\sigma_{LO} = f_{a/p} \otimes f_{b/p} \otimes d\hat{\sigma}_{LO} \quad \rightarrow \text{LHE}$$

$$\begin{aligned}
\sigma_{NLO} &= f_{a/p} \otimes f_{b/p} \otimes \int_m d\hat{\sigma}_V \\
&+ f_{a/p} \otimes f_{b/p} \otimes \int_{m+1} (d\hat{\sigma}_R - d\hat{\sigma}_{CS}) \\
&+ f_{a/p} \otimes f_{b/p} \otimes \int_m d\hat{\sigma}_I \\
&+ KP_{a/p} \otimes KP_{b/p} \int_m d\hat{\sigma}_{KP} \\
&\rightarrow \text{Histograms}
\end{aligned}$$

THE HELAC-NLO ADVENTURE

- 2006 `OPP`: The method that enables us to think seriously about NLO calculations.

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Based on previous work by Bern, Dixon, Kosower, Britto, Cachazo, Feng.

Z. Bern, L. J. Dixon, D. C. Dunbar and D. A. Kosower, Nucl. Phys. B **425** (1994) 217 [arXiv:hep-ph/9403226].

R. Britto, F. Cachazo and B. Feng, Nucl. Phys. B **725** (2005) 275 [arXiv:hep-th/0412103].

Complete framework: numerical (fast) & algebraic (stable)

G. Ossola, C. G. Papadopoulos and R. Pittau, Nucl. Phys. B **763** (2007) 147 [arXiv:hep-ph/0609007].

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G. Ossola, C. G. Papadopoulos and R. Pittau, JHEP **0803** (2008) 042 [arXiv:0711.3596 [hep-ph]].

G. Ossola, C. G. Papadopoulos and R. Pittau, JHEP **0805** (2008) 004 [arXiv:0802.1876 [hep-ph]].

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A. van Hameren, C. G. Papadopoulos and R. Pittau, JHEP **0909** (2009) 106 [arXiv:0903.4665 [hep-ph]].

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- 2008 `HELAC-1LOOP`: Based on `HELAC` to produce virtual one-loop amplitudes
- 2009 `HELAC-Dipoles`: Based on `HELAC` to *automatically* produce Catani-Seymour dipoles, I-operator, KP-operator, arbitrary masses

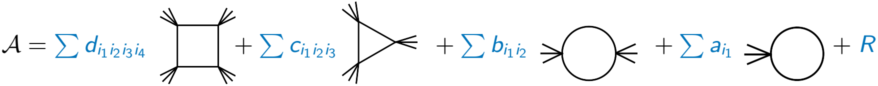
M. Czakon, C. G. Papadopoulos and M. Worek, JHEP **0908** (2009) 085 [arXiv:0905.0883 [hep-ph]].

Theoretical framework

THEORETICAL FRAMEWORK - VIRTUAL CORRECTIONS

We organize our one-loop calculation within the framework of the OPP method :

1. decompose amplitudes into a basis of scalar integrals:



$$\mathcal{A} = \sum d_{i_1 i_2 i_3 i_4} + \sum c_{i_1 i_2 i_3} + \sum b_{i_1 i_2} + \sum a_{i_1} + R$$

$a, b, c, d \rightarrow$ cut-constructible part $\qquad$ $R \rightarrow$ rational terms

$$\mathcal{A} = \sum_{I \subset \{0,1,\cdots,m-1\}} \int \frac{\mu^{(4-d)} d^d q}{(2\pi)^d} \frac{\bar{N}_I(\bar{q})}{\prod_{i \in I} \bar{D}_i(\bar{q})}$$

THEORETICAL FRAMEWORK - VIRTUAL CORRECTIONS

We organize our one-loop calculation within the framework of the OPP method :

2. evaluate the coefficients of the expansion at the *integrand* level:

$$\begin{aligned}
N(q) &= \sum_{i_0<i_1<i_2<i_3}^{m-1} \left[d(i_0,i_1,i_2,i_3) + \tilde{d}(q;i_0,i_1,i_2,i_3)\right] \prod_{i\neq i_0,i_1,i_2,i_3}^{m-1} D_i \\
&+ \sum_{i_0<i_1<i_2}^{m-1} \left[c(i_0,i_1,i_2) + \tilde{c}(q;i_0,i_1,i_2)\right] \prod_{i\neq i_0,i_1,i_2}^{m-1} D_i \\
&+ \sum_{i_0<i_1}^{m-1} \left[b(i_0,i_1) + \tilde{b}(q;i_0,i_1)\right] \prod_{i\neq i_0,i_1}^{m-1} D_i \\
&+ \sum_{i_0}^{m-1} \left[a(i_0) + \tilde{a}(q;i_0)\right] \prod_{i\neq i_0}^{m-1} D_i
\end{aligned}$$

$\tilde{a}, \tilde{b}, \tilde{c}, \tilde{d}$ are "spurious" terms (vanish upon integration). Their q-dependence is known

Ossola, Papadopoulos and Pittau, Nucl. Phys. B 763, 147 (2007)

THEORETICAL FRAMEWORK - VIRTUAL CORRECTIONS

We organize our one-loop calculation within the framework of the OPP method :

3. compute the rational terms $R = R_1 + R_2$:

- R_1: originates from the ϵ dependence of *denominators*

$$D_i \to \bar{D}_i - \tilde{q}^2$$

↪ computable within the framework of OPP reduction

Ossola, Papadopoulos and Pittau, JHEP 0805 (2008) 004

- R_2: originates from the ϵ dependence of *numerators*

$$\bar{q} = q + \tilde{q} \qquad \bar{\gamma}_\mu = \gamma_\mu + \tilde{\gamma}_\mu \qquad \bar{g}^{\mu\nu} = g^{\mu\nu} + \tilde{g}^{\mu\nu}$$

↪ computable with effective tree-level Feynman rules

Draggiotis, Garzelli, Papadopoulos and Pittau, arXiv:0903:0356 [hep-ph]

Garzelli, Malamos and Pittau, arXiv:0910.3130 [hep-ph]

THEORETICAL FRAMEWORK - COMPLEX MASS SCHEME

- Resumed corrections in two-point functions and consistency of scattering matrix elements Veltman 1962
- Naive schemes may violate badly WI and result to obviously wrong results Phys. Lett. B **349** (1995) 367
- Fixed width schemes: partially satisfying WI Argyres *et al.* Phys. Lett. B **358** (1995) 339
- Fermion-loop scheme: WI consistent Beenakker *et al.* Nucl. Phys. B **500** (1997) 255
- CMS: complex renormalized parameters Denner *et al.* Nucl. Phys. B **560** (1999) 33

  Top-quark propagator:

  $(\not{p} - m_t + i\epsilon)^{-1}$ with the resumed one $(\not{p} - \mu_t + i\epsilon)^{-1}$

  $\mu_t^2 = m_t^2 - i m_t \Gamma_t$
- Renormalization Beenakker *et al.* Nucl. Phys. B **653** (2003) 151

  $\frac{\delta m_t}{m_t} = -\frac{\alpha_s}{3\pi}\left[3\Delta + 4\right] \rightarrow \frac{\delta \mu_t}{\mu_t}$ $\Delta = \frac{\Gamma(1+\epsilon)}{\epsilon}\left(\frac{4\pi\mu^2}{m_t^2}\right)$ with $m_t^2 \rightarrow \mu_t^2$

THEORETICAL FRAMEWORK - REAL CORRECTIONS

Subtraction terms encoding IR/collinear divergences:

$$\sigma^{NLO} = \int_m d\sigma^B + \int_{m+1} d\sigma^R - \int_{m+1} d\sigma^A + \int_{m+1} d\sigma^A + \int_m d\sigma^V$$

$$\hookrightarrow \quad \int d\sigma^B + \int_{m+1} \left[d\sigma^R - d\sigma^D \right] + \int_m \left[d\sigma^V + d\sigma^I + d\sigma^{KP} \right]$$

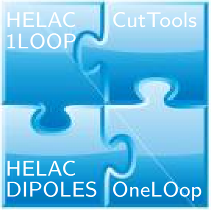
Catani-Seymour dipole formalism

Catani, Seymour, Nucl. Phys. B485, 291 (1997)
Catani, Dittmaier, Seymour, Trocsanyi, Nucl. Phys. B627, 189 (2002)

extended to arbitrary helicity eigenstates of the external partons

Czakon, Papadopoulos, Worek, arXiv:0905.0883 [hep-ph]

The HELAC-NLO system



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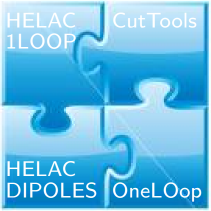
The HELAC-NLO system



HELAC-1LOOP

- evaluation of loop numerators $N(q)$ and rational terms R_2

CutTools

- reduction of tensor integrals, determination of OPP coefficient and R_1

OneLOop

- evaluation of scalar integrals

Ossola, Papadopoulos and Pittau, JHEP **0803** (2008) 042 [arXiv:0711.3596 [hep-ph]]
Van Hameren, Papadopoulos and Pittau, JHEP **0909** (2009) 106 [arXiv:0903.4665 [hep-ph]]

HELAC-DIPOLES

- Catani-Seymour dipole subtraction for massless and massive cases

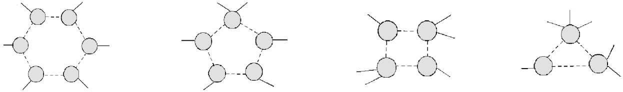
Czakon, Papadopoulos and Worek, JHEP **0908**, 085 (2009) [arXiv:0905.0883 [hep-ph]]

Integration over phase space performed with KALEU (adaptive) and cross-checked with PHEGAS (multichannel)

THE ONE-LOOP CALCULATION IN A NUTSHELL

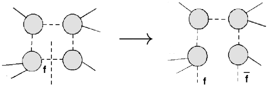
The computation of $pp(p\bar{p}) \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}$ involves up to six-point functions.
The most generic integrand has therefore the form

$$\mathcal{A}(q) = \sum \underbrace{\frac{N_i^{(6)}(q)}{\bar{D}_{i_0}\bar{D}_{i_1}\cdots\bar{D}_{i_5}}} + \underbrace{\frac{N_i^{(5)}(q)}{\bar{D}_{i_0}\bar{D}_{i_1}\cdots\bar{D}_{i_4}}} + \underbrace{\frac{N_i^{(4)}(q)}{\bar{D}_{i_0}\bar{D}_{i_1}\cdots\bar{D}_{i_3}}} + \underbrace{\frac{N_i^{(3)}(q)}{\bar{D}_{i_0}\bar{D}_{i_1}\bar{D}_{i_2}}} + \cdots$$



In order to apply the OPP reduction, `HELAC` evaluates numerically the numerators $N_i^6(q), N_i^5(q), \ldots$ with the values of the loop momentum q provided by `CutTools`

- generates all inequivalent partitions of 6,5,4,3... blobs attached to the loop, and check all possible flavours (and colours) that can be consistently running inside
- hard-cuts the loop (q is fixed) to get a $n+2$ *tree-like* process



The R_2 contributions (rational terms) are calculated in the same way as the tree-order amplitude, taking into account *extra vertices*

OTHER FEATURES

Finite width

- complex-mass scheme adopted for intermediate top quarks

Colour/helicity Monte Carlo

- sum over colours and helicities performed with Monte Carlo sampling

One-loop reweighting

- LO+V result obtained by *re-weighting* a sample of *tree-level unweighted* events

Stability checks

- check of Ward identity for virtual corrections
- check of independence on α_{max} cutoff for real corrections

Phenomenological Results

HELAC-NLO

- $pp \to t\bar{t}b\bar{b}$: proof-of-concept

  G. Bevilacqua, M. Czakon, C. G. Papadopoulos, R. Pittau and M. Worek, JHEP **0909** (2009) 109 [arXiv:0907.4723 [hep-ph]].

  M. Worek, JHEP **1202** (2012) 043 [arXiv:1112.4325 [hep-ph]].
- $pp \to t\bar{t} + j + j$: one of the most advanced

  G. Bevilacqua, M. Czakon, C. G. Papadopoulos and M. Worek, Phys. Rev. Lett. **104** (2010) 162002 [arXiv:1002.4009 [hep-ph]].

  G. Bevilacqua, M. Czakon, C. G. Papadopoulos and M. Worek, Phys. Rev. D **84** (2011) 114017 [arXiv:1108.2851 [hep-ph]].
- $pp \to W^+W^-b\bar{b}$ including $(t\bar{t})$: finite width and complex masses

  G. Bevilacqua, M. Czakon, A. van Hameren, C. G. Papadopoulos and M. Worek, JHEP **1102** (2011) 083 [arXiv:1012.4230 [hep-ph]].
- $pp \to t\bar{t}t\bar{t}$: BSM phenomenology

  G. Bevilacqua and M. Worek, JHEP **1207** (2012) 111 [arXiv:1206.3064 [hep-ph]].
- $pp \to t\bar{t} + j \oplus$ `POWHEG`

  A. Kardos, C. Papadopoulos and Z. Trocsanyi, Phys. Lett. B **705** (2011) 76 [arXiv:1101.2672 [hep-ph]].
- $pp \to t\bar{t} + H \oplus$ `POWHEG`

  M. V. Garzelli, A. Kardos, C. G. Papadopoulos and Z. Trocsanyi, Europhys. Lett. **96** (2011) 11001 [arXiv:1108.0387 [hep-ph]].
- $pp \to t\bar{t} + Z/W^{\pm} \oplus$ `POWHEG`

  M. V. Garzelli, A. Kardos, C. G. Papadopoulos and Z. Trocsanyi, arXiv:1208.2665 [hep-ph].

OTHER NLO RESULTS

- $pp \to 4$ jets, $pp \to Z/W + 4$ jets (`Blackhat` $\oplus$ `Sherpa`)

  Z. Bern, G. Diana, L. J. Dixon, F. Febres Cordero, S. Hoeche, D. A. Kosower, H. Ita and D. Maitre *et al.*, Phys. Rev. Lett. **109**, 042001 (2012) [arXiv:1112.3940 [hep-ph]]

  H. Ita, Z. Bern, L. J. Dixon, F. Febres Cordero, D. A. Kosower and D. Maitre, Phys. Rev. D **85** (2012) 031501 [arXiv:1108.2229 [hep-ph]].

  C. F. Berger, Z. Bern, L. J. Dixon, F. Febres Cordero, D. Forde, T. Gleisberg, H. Ita and D. A. Kosower *et al.*, Phys. Rev. Lett. **106** (2011) 092001 [arXiv:1009.2338 [hep-ph]].

  F. Siegert, S. Hoeche, F. Krauss and M. Schonherr, arXiv:1206.4873 [hep-ph].

- $pp \to W^+W^- + 2$ jets (`GoSam` $\oplus$ `Sherpa`)

  N. Greiner, G. Heinrich, P. Mastrolia, G. Ossola, T. Reiter and F. Tramontano, Phys. Lett. B **713** (2012) 277 [arXiv:1202.6004 [hep-ph]].

- $pp \to t\bar{t} \to W^+W^-b\bar{b}$ & $pp \to W^+W^+ 2$ jets in VBF (`OpenLoops`)

  A. Denner, S. Dittmaier, S. Kallweit and S. Pozzorini, arXiv:1207.5018 [hep-ph].

  A. Denner, L. Hosekova and S. Kallweit, arXiv:1209.2389 [hep-ph].

- $p\bar{p} \to Wjj \oplus$ aMC@NLO (`MadLoop` $\oplus$ `MadFKS` $\oplus$ `MadGraph`)

  R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, R. Pittau and P. Torrielli, JHEP **1202** (2012) 048 [arXiv:1110.5502 [hep-ph]].

- $pp \to H + 2$ jets $\oplus$ `POWHEG`

  J. M. Campbell, R. K. Ellis, R. Frederix, P. Nason, C. Oleari and C. Williams, JHEP **1207** (2012) 092 [arXiv:1202.5475 [hep-ph]].

- $pp \to Z + 2$ jets $\oplus$ `POWHEG`

  B. Jager, S. Schneider and G. Zanderighi, JHEP **1209** (2012) 083 [arXiv:1207.2626 [hep-ph]].

QUESTIONS

- Automation → Reliability, Speed, Efficiency
- Utility in analysis → Parton Showering ⊗ event formats
- Merging ⊕ Matching